The fate of carbon and nutrients exported out of the Southern Ocean

Judith Hauck
Andrew Lenton, Clothilde Langlais, Richard Matear
„Southern Ocean nutrient supply accounts for about three-quarters of biological production north of 30°S“

(Sarmiento et al., 2004)
Southern Ocean nutrient supply accounts for about three-quarters of biological production north of 30°S.

The Variable Southern Ocean Carbon Sink

Nicolas Gruber, Peter Landschützer, and Nicole S. Lovenduski

Furthermore, this region acts also as the key gatekeeper controlling the supply of nutrients to the low latitude oceans, and thus the magnitude of low latitude productivity in the past, present and future (Sarmiento et al. 2004; Matsumoto et al. 2002; Moore et al. 2018).

Models suggest that vertical exchange within the Southern Ocean is responsible for supplying nutrients that fertilize three-quarters of the biological production in the global ocean north of 30°S (Sarmiento et al., 2004, Marinov et al., 2006).
Previous studies

“Southern Ocean nutrient supply accounts for about three quarters of biological production north of 30°S”

Sarmiento et al., 2004

**The Southern Ocean biogeochemical divide**

I. Marinov\(^1\), A. Gnanadesikan\(^2\), J. R. Toggweiler\(^2\) & J. L. Sarmiento\(^1\)

**Nutrient supply**

Preindustrial results at equilibrium!

**Carbon sequestration**

Marinov et al., 2006
Southern Ocean – decoupling of anthropogenic CO$_2$ uptake and storage

>50% of Southern Ocean C$_{\text{ant}}$ in SAMW and AAIW (Langlais et al., Sci. Rep., 2017)
Aims of this talk

Provide a similar concept for carbon fluxes

Spoiler: Southern Ocean nutrient supply to low-latitudes is overestimated
Transient response – large decadal variability / future change

Large decadal variability of Southern Ocean CO₂ uptake
Landschützer et al., 2015

Panassa et al (2018): Significant increase in nitrate concentration in AAIW based on Polarstern data

Iida et al., 2013; Ayers & Strutton, 2013; Hoppema et al., 2015; Pardo et al., 2017
Regulated Ecosystem Model (REcoM2)

Based on Schartau et al., BG, 2007
Non-Redfield model
Explicit sinking

Hauck et al., GBC, 2013
Hauck et al., 2012, 2016
Model Experiments

1. Control
2. No bio in Southern Ocean

Hauck et al., GBC, 2018
Model Experiments

1. Control
2. No bio in Southern Ocean
3. No bio + no gas-ex in SO

Hauck et al., GBC, 2018
Model Experiments

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Hauck et al., GBC, 2018
Model Experiments

MITgcm-REcoM2 (Hauck et al., 2013; 2015; 2016)

JRA55 reanalysis 1958-2016

Spin-up: two cycles of JRA forcing, third cycle until 2005

Experiment: keep atmospheric forcing and CO₂ concentration constant at 2005 levels
Positive: Southern Ocean primary production $\rightarrow$ increase in DIN
Negative: Southern Ocean primary production $\rightarrow$ decrease in DIN

Negative DIN anomaly in SO surface and north of 40°S surface and to $\sim$3500 m.
Positive DIN anomaly in SO subsurface to bottom
Results – Perturbations of nutrient fields, year 196-200

Positive: Southern Ocean primary production $\rightarrow$ increase in DIN
Negative: Southern Ocean primary production $\rightarrow$ decrease in DIN

DIN anomaly spreads all over the Atlantic in 200 years
Pacific shadow zone

Abyssal ocean overturning shaped by seafloor distribution

De Lavergne et al., 2017
Vertically-Integrated Net Primary Production

No nutrient utilization in Southern Ocean:
7.0 PgC/y loss south of 40°S
3.0 PgC/y gain north of 40°S → locally 10% increase

→ 43% compensation on 200-year time-scale
→ 39% for export
Vertically-Integrated Net Primary Production

No nutrient utilization in Southern Ocean:

Locally 32% increase of diatom NPP (87% compensation)

Reinforcement of nano-NPP rather than compensation

'silicate leakage’
Change in mean Southern Ocean surface nutrients

DIN: $15 \text{ mmol m}^{-3} \rightarrow 26 \text{ mmol m}^{-3}$ ($+75\%$)
DSi: $14 \text{ mmol m}^{-3} \rightarrow 50 \text{ mmol m}^{-3}$ ($+255\%$)
DFe: $0.15 \text{ µmol m}^{-3} \rightarrow 0.64 \text{ µmol m}^{-3}$ ($+340\%$)

100% change in DIN would lead to 13% in NPP north of 40°S

„Southern Ocean nutrient supply accounts for about three quarters of biological production north of 30°S“

Sarmiento et al., 2004
Previous studies

„Southern Ocean nutrient supply accounts for about three quarters of biological production north of 30°S“
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33 – 75% of low latitude productivity is sustained by nutrient export from SAMW
Palter et al., 2010

27% of midlatitude and subpolar North Atlantic fuelled by nutrients last utilized in the Southern Ocean, with even lower numbers elsewhere
Holzer and Primeau, 2013
Previous studies

Signal depends on direction of perturbation

Non-linear state-dependency

Primeau et al., 2013

Primeau et al., 2013

Increase in SO production

Decrease

unperturbed
Previous studies

Signal depends on direction of perturbation
Non-linear state-dependency

NPP frac sustained by SO nutrients

Sarmiento et al

Primeau et al., 2013

Increase in SO production
Decrease

This study
Carbon
Results – Perturbations of DIC fields, year 196-200

Atlantic

Pacific

DIC (mmol/m3) contrib. bio

DIC (mmol/m3) contrib. phys
The fate of carbon

-0.52 PgC/yr
Uptake low, as atm. CO₂ is constant

-1.14 PgC/yr (uptake)

+0.62 PgC/yr (outgassing)

0.2 PgC/yr (outgassing)

0.57 PgC/yr (tendency to outgas)

-0.55 PgC/yr (tendency to uptake)
The fate of carbon

Bio and phys effects nearly balance, but

Changes in SO bio, uncompensated by SO physics
Moore et al. (2018)

Changes in SO phys, incompletely compensated by bio
LeQuéré et al. (2007), Hauck et al. (2013)
The fate of carbon

Atm CO₂ increasing with rate of increase (2000-2010) = 1.98 ppm/year
The fate of carbon

Larger uptake due to higher and increasing atm CO₂

SO turns from outgassing to uptake after ~50 years

→ Smaller uptake

Southern Ocean carbon pumps lead to outgassing of 0.47 PgC/yr
Implications for carbon uptake

Compensation = \frac{-\text{CO}_2 \text{ flux north of } 40^\circ \text{S}}{\text{CO}_2 \text{ flux south of } 40^\circ \text{S}}

Compensation of CO2Flx

1: complete compensation

0: SO C-pumps do not lead to change north of 40°S
Implications for carbon uptake

Compensation = \[ \frac{-\text{CO}_2 \text{ flux north of 40°S}}{\text{CO}_2 \text{ flux south of 40°S}} \]

1: complete compensation

**Physical pump:** 90% compensation

**Biological pump:** 50% compensation

0: SO C-pumps do not lead to change north of 40°S
Implications for carbon uptake

Compensation = \frac{-\text{CO}_2 \text{ flux north of } 40^\circ\text{S}}{\text{CO}_2 \text{ flux south of } 40^\circ\text{S}}

- Biological pump stores CO$_2$ for longer than physical pump
  - Incomplete compensation of NPP
  - Sinking of particles to deeper depths

Feedbacks in the ocean carbon sink due to potential future changes in
  - physically-driven CO$_2$ uptake occur faster and are nearly balanced after 200 years
  - biological C-pump occur slower but last longer
Summary

(a) active SO biology

1. CO₂
2. DIC ↑
3. nuts ↓ NPP ↓ DIC ↓
4. CO₂
5. CO₂
6. DIC ↓
7. CO₂

(b) active abiotic SO CO₂ flux

Physical pump: CO₂ outgassing, 90% reventilated after 200 years
Biological pump: CO₂ uptake, 50% reventilated after 200 years
Net Primary Production perturbation: 40% compensation on 200 year time-scale

Hauck et al., 2018, GBC
Timescales of subduction and reventilation

\[ T(50\%) = 92 \text{ yr} \]
\[ T(75\%) = 272 \text{ yr} \]

\[ T_{\text{min}} = 28 \text{ years} \]

50% ~ 100 years

70% ~ 200 years

Rodgers et al., GRL, 2003
Results – timescale of reventilation

Emergence of signal in equatorial

Atlantic: \( \sim 15 \) years

Pacific: \( \sim 30 \) years

Somewhat shorter time-scale than Rodgers et al, because:
- Rodgers neglect stochastic terms in Lagrangian models to account for transport by eddies (Shah et al., 2017)
- Includes perturbation of surface
- Rodgers stricter definition of eq. Pac.
Si remineralization deeper than for DIN

Fe stark contrast deep
Atl and Pac

SO NPP → accumulation of Fe in surface Atl
The fate of carbon

DIC CO₂ flux

(c) DIC contrib

(d) CO₂ flux

mmol m⁻² d⁻¹

HELMHOLTZ
SO active biology $\rightarrow$ negative NPP anomaly $\rightarrow$ positive DIC anomaly $\rightarrow$ positive CO$_2$ flux anomaly (more outgassing or less uptake)
The fate of carbon

SO active biology $\rightarrow$ negative NPP anomaly $\rightarrow$ positive DIC anomaly $\rightarrow$ positive CO$_2$ flux anomaly (more outgassing or less uptake)
SO active biology $\rightarrow$ upwelling of DIC depleted water $\rightarrow$ negative DIC anomaly $\rightarrow$ negative CO$_2$ flux anomaly (less outgassing or more uptake)
Previous studies

Holzer and Primeau, 2013

Blue: fraction of NPP sustained by SO nutrients

27% North Atlantic

Holzer and Primeau, 2013
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27% of midlatitude and subpolar North Atlantic fuelled by nutrients last utilized in the Southern Ocean, with even lower numbers elsewhere
Holzer and Primeau, 2013

Increasing nutrient utilization in the Southern Ocean resulted in a larger fraction of nutrients last utilized in the Southern Ocean (up to 45%), but decreaded the overall productivity.
Holzer and Primeau, 2013

Non-linear response of productivity outside the Southern Ocean to perturbations within the Southern Ocean (increase/decrease of nutrient utilization)
Primeau et al., 2013
Transport of $C_{\text{ant}}$ into the ocean interior through:
Northward-Ekman transport, and formation of Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW)
>50% of Southern Ocean $C_{\text{ant}}$ in SAMW and AAIW (Langlais et al., 2017)